Determining supernova unknowns with the diffuse supernova neutrino background

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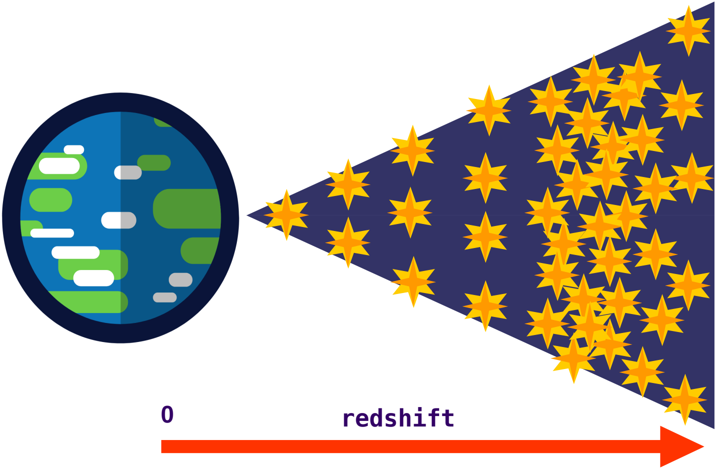
Overview

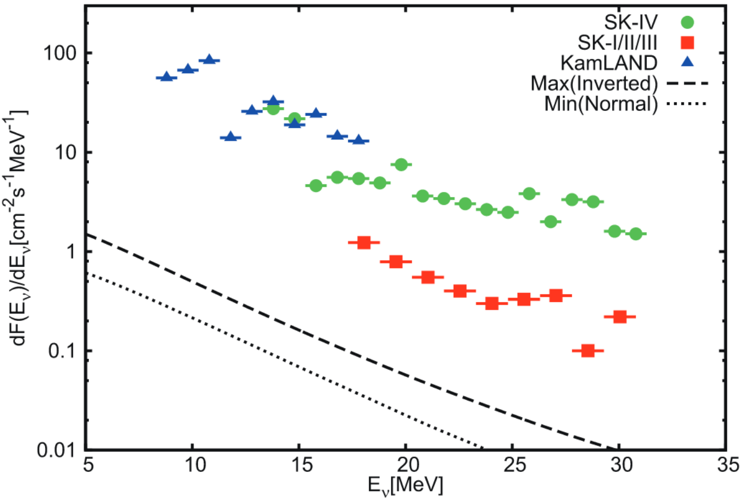
1. Neutrino emission from the core-collapse supernovae
2. Diffuse supernova neutrino background
3. The DSNB detection and measurement
4. Conclusions

Diffuse supernova neutrino background



kpc	Mpc	Gpc
$\sim$ 3 SNe/100 yr	$\sim$ 1 SNe/yr	$\sim$ 1 SNe/s
high statistics	few events	DSNB

Inevitable detection within next 10-15 years



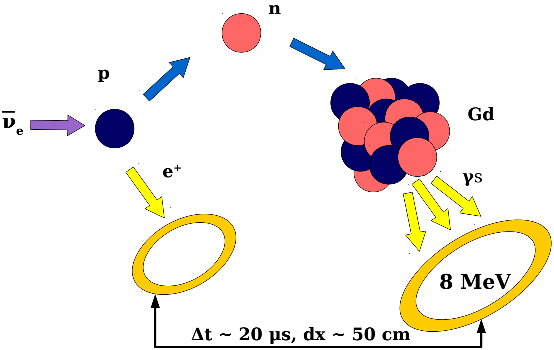
Super Kamiokande (Gd, 2020) $\sim 3\ \sigma$ within 10 yrs

SK Collaboration, arXiv:1111.5031, Nakazato et al., arXiv:1503.01236

Gadolinium sulfate enrichment

Neutron tagging in Gd-enriched water Cherenkov detectors

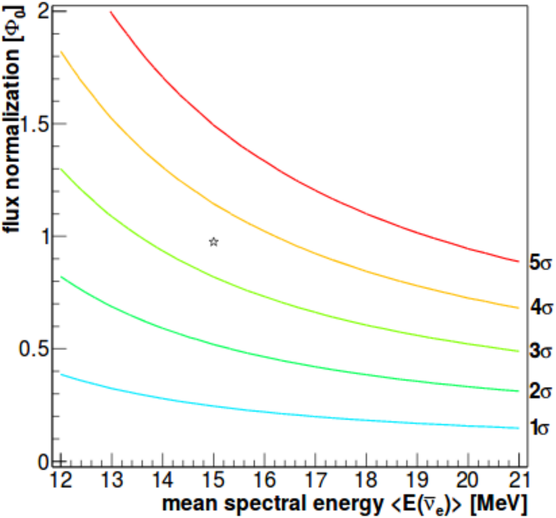
- concidence detection of positron and neutron
- high cross section for neutron capture ~4900 barn
- elimination of spallation background
- reduction of invisible muon background



Beacom and Vagins, arXiv:0309300

Inevitable detection within next 10-15 years

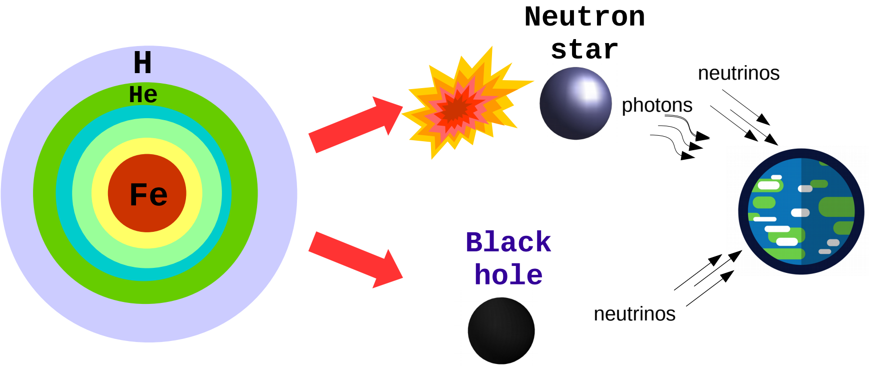
JUNO (2021) $\sim 3\,\sigma$ within 10 yrs



JUNO collaboration, arXiv:1507.05613

Neutrinos:

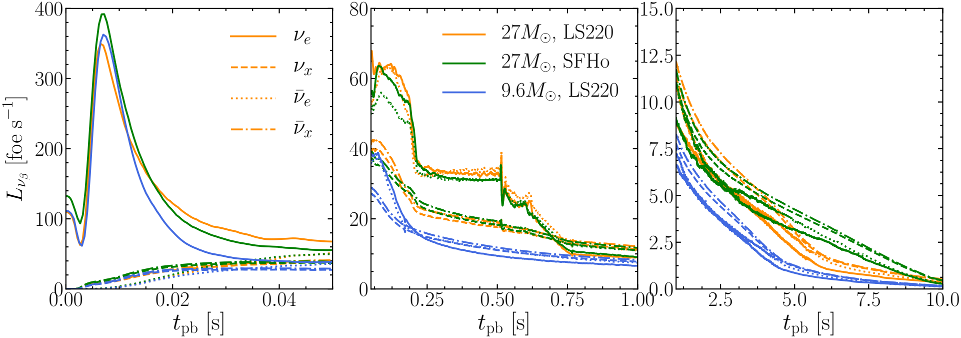
- play a crucial role in the explosion mechanism
- can reveal the interior conditions of a collapsing star
- are the only messengers from the collapse to a black hole (+ GW)



Neutrino emission from the core-collapse supernovae

1 foe = 10^{51} ergs

CC-SN progenitors

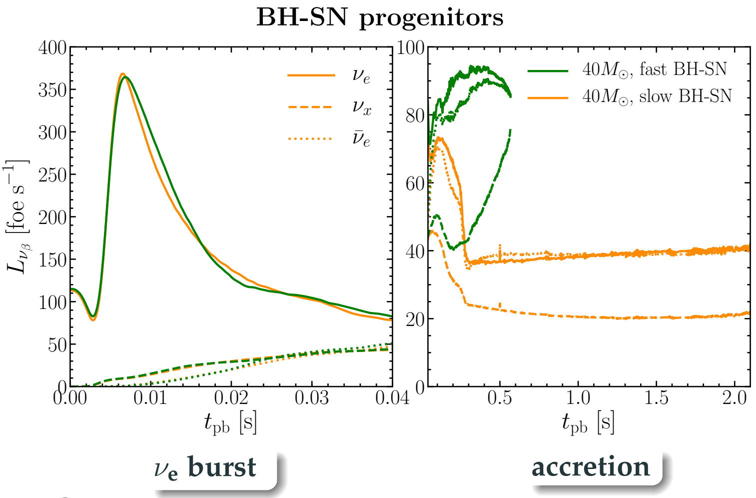


ν_e **burst** | **accretion** | **cooling**

CC-SN

equation of state = LS220 or SFHo, mass = 9.6 $M_\odot$ or 27 $M_\odot$

Garching core-collapse supernova archive



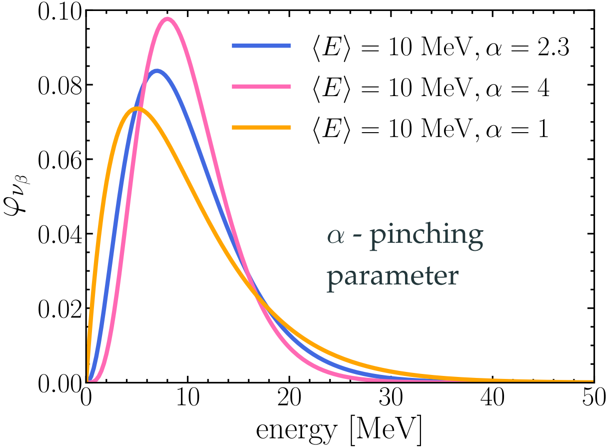
BH-SN

equation of state = LS220, mass = 40 $M_\odot$, t_{BH} = 0.57 s or 2.1 s

Garching core-collapse supernova archive

Neutrino fluxes

Neutrino energy distribution



Differential neutrino flux

$$f^0_{\nu_\beta}(E, t_{\rm pb}) = \frac{L_{\nu_\beta}(t_{\rm pb})}{4\pi r^2}\frac{\varphi_{\nu_\beta}(E, t_{\rm pb})}{\langle E_{\nu_\beta}(t_{\rm pb})\rangle} = \frac{F^0_{\nu_\beta}(E, t_{\rm pb})}{4\pi r^2}$$

Keil et al., arXiv:0208035

Equation of motion for supernova neutrinos

$$\frac{d}{dr}\rho = -i[H, \rho],$$

vacuum **matter** **neutrino - neutrino**

$$H = U^{\dagger} diag(m_1^2, m_2^2, m_3^2)U + diag(V_{CC}, 0, 0) + \int d^3p'(\rho - \bar{\rho})(1 - v' \cdot v)$$

Mirizzi et al., arXiv:1508.00785

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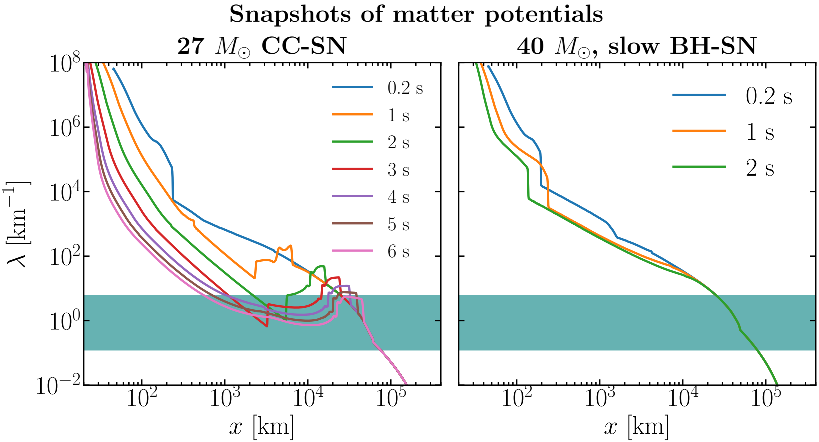
Mirizzi et al., arXiv:1508.00785 , Lunardini and Tamborra, arXiv:1205.6292

Matter potentials

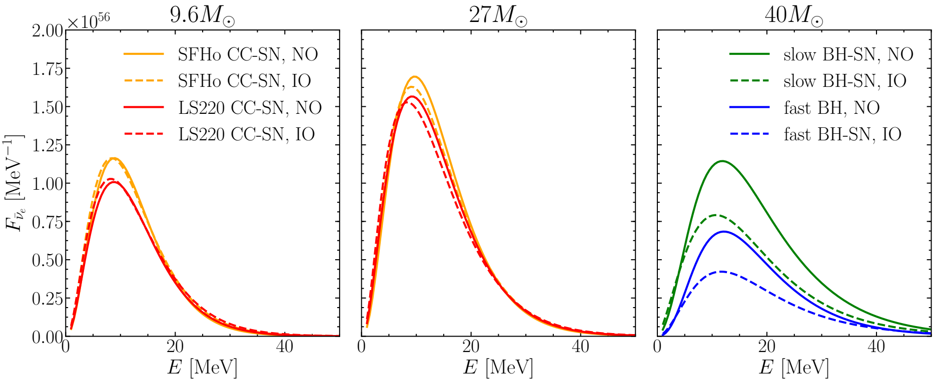


Resonance potential

$$\lambda_{res} = \frac{\cos 2\theta_{13} \Delta m^2}{2E} \approx \cos 2\theta_{13} \left(\frac{\Delta m^2}{\mathrm{eV}^2}\right)\left(\frac{\mathrm{GeV}}{E}\right) \ [\mathrm{km}^{-1}]$$

Wolfenstein, Phys. Rev. D **17**, 2369 , Dighe and Smirnov, arXiv:9907423, Mikheev and Smirnov, Nuovo Cim. C9 (1986) 17–26.

Time-integrated neutrino fluxes



	CC-SN	BH-SN
high-energy neutrinos	fewer	more
distinguish progenitor	no	yes
distinguish mass ordering	no	yes

Diffuse supernova neutrino background

Diffuse supernova neutrino background (DSNB)

cosmological supernovae rate

fraction of black-hole-forming progenitors

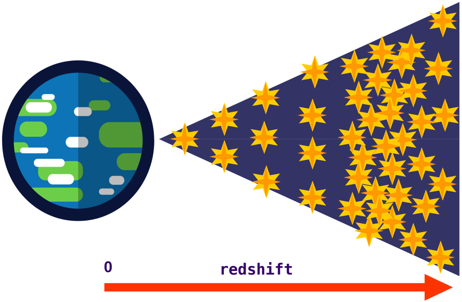
$$\Phi_{\nu_\beta}(E) = \frac{c}{H_0}\int dM \int dz \frac{R_{\rm SN}(z,M)}{\sqrt{\Omega_M(1+z)^3+\Omega_\Lambda}}\left[f_{\rm CC-SN}F_{\nu_\beta,\rm CC-SN}(E',M) + f_{\rm BH-SN}F_{\nu_\beta,\rm BH-SN}(E',M)\right]$$

fraction of neutron-star-forming progenitors

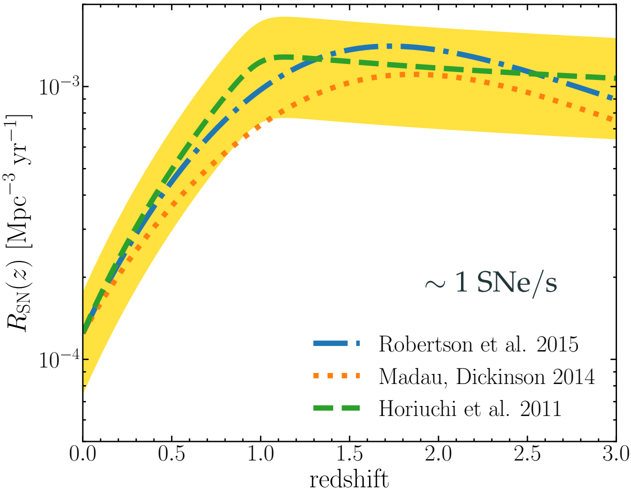
oscillated neutrino flux
E′ = (1+z)E

The DSNB is sensitive to:

- $R_{\rm SN}$
- $f_{\rm BH-SN}$
- neutrino mass ordering
- equation of state
- mass accretion rate in BH-SN

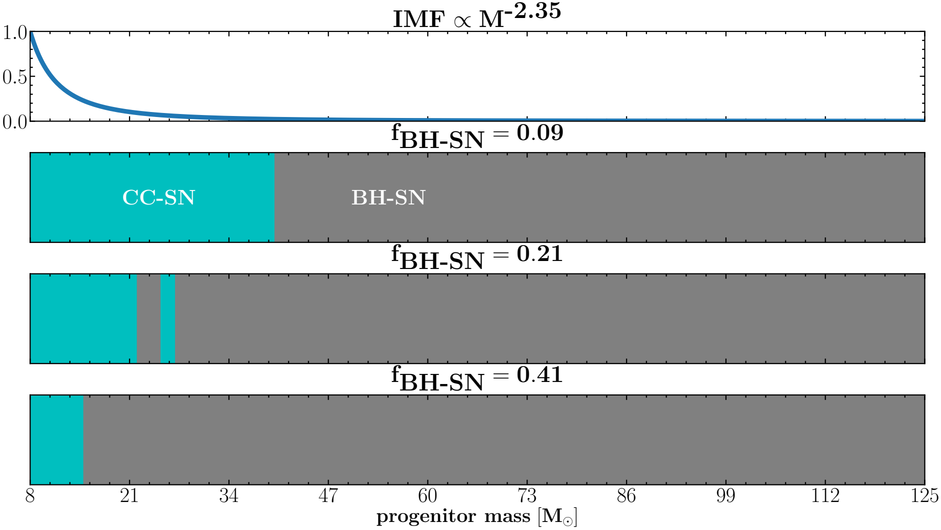


Cosmological supernovae rate

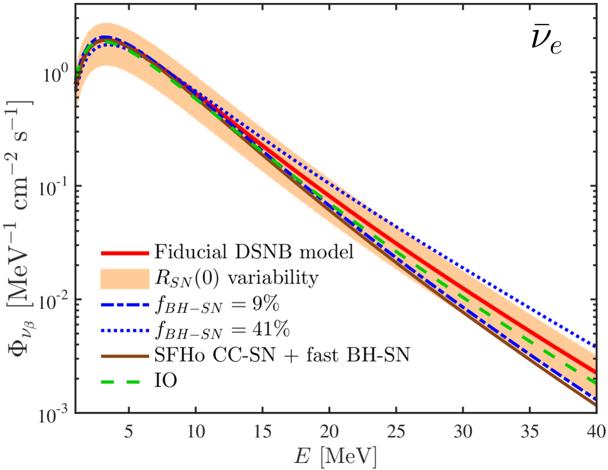


The supernovae rate influences the normalization of the DSNB.

Fraction of BH-forming progenitors



Ertl et al. arXiv:1503.07522, Sukhbold et al. arXiv:1510.04643, Adams et al. arXiv:1610.02402, Heger et al. arXiv:0112059

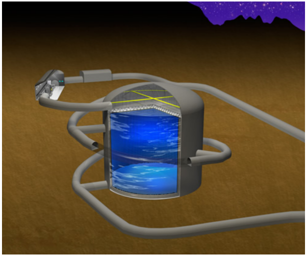


Fiducial DSNB model: $R_{\mathrm{SN}}(0) = 1.25 \times 10^{-4}\ \mathrm{Mpc}^{-3}\ \mathrm{yr}^{-1}, f_{\mathrm{BH-SN}} = 0.21$, equation of state = LS220, mass accretion rate = slow

The DSNB detection and measurement

Future generation neutrino detectors

Hyper-Kamiokande (2026(8?))



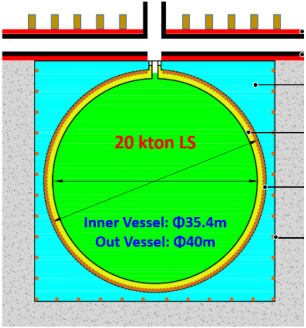
fiducial volume

2×187 kton

main detection channel

$$\bar{\nu}_e + \mathrm{p} \to e^+ + \mathrm{n}$$

JUNO (2021)



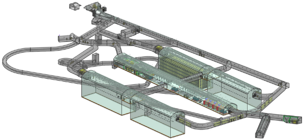
fiducial volume

17 kton

main detection channel

$$\bar{\nu}_e + \mathrm{p} \to e^+ + \mathrm{n}$$

DUNE (2027)



fiducial volume

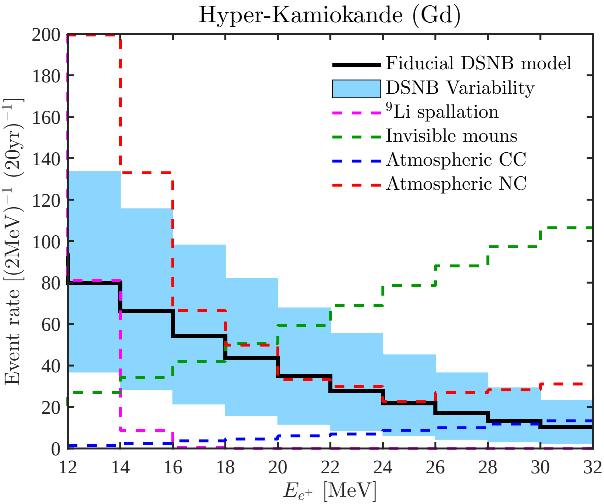
4×10 kton

main detection channel

$$\nu_e + \mathrm{Ar} \to e^- + {}^{40}\mathrm{K}^*$$

HK Design Report, JUNO Conceptual Design Report, DUNE science

The DSNB event rates

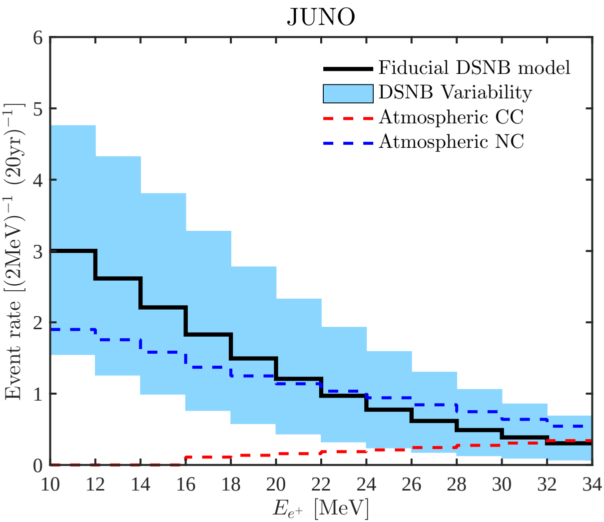


Detectability prospects for 20 yrs

- HK (Gd) with NC: $\sim 10\ \sigma$
- HK (Gd) w/o NC: $\sim 12.5\ \sigma$

BG rates: HK Design Report, K. Huang PhD thesis

The DSNB event rates



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BG rates: JUNO collaboration, arXiv:1507.05613

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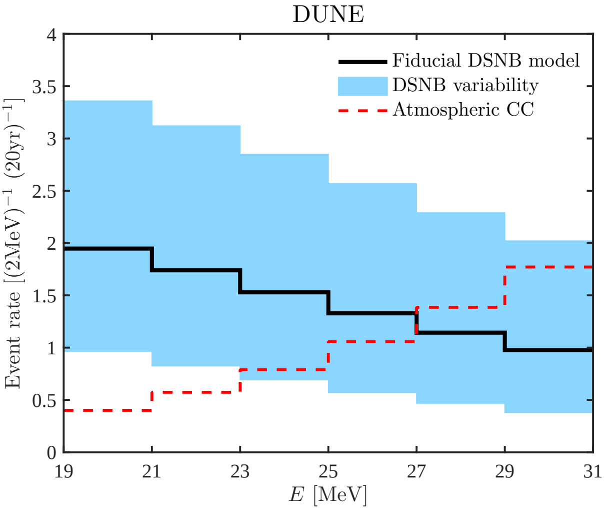

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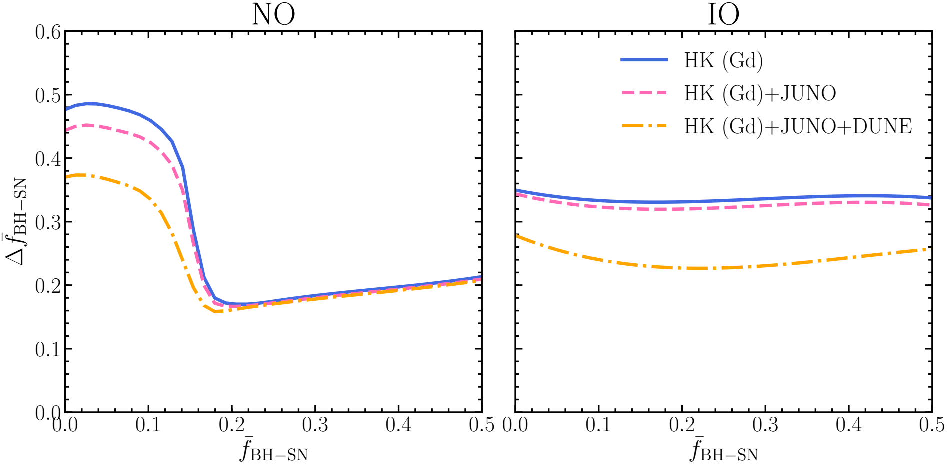
- HK (Gd) w/o NC: $\sim 12.5\ \sigma$
- JUNO: $\sim 3.4\ \sigma$
- DUNE: $\sim 2.8\ \sigma$

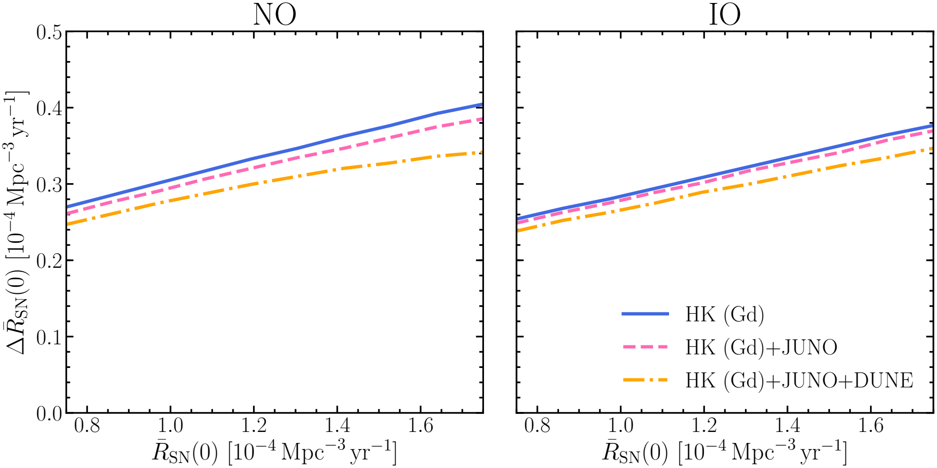
BG rates: Coco et al., arXiv:0408031

Expected 1σ uncertainty: fraction of BH forming progenitors



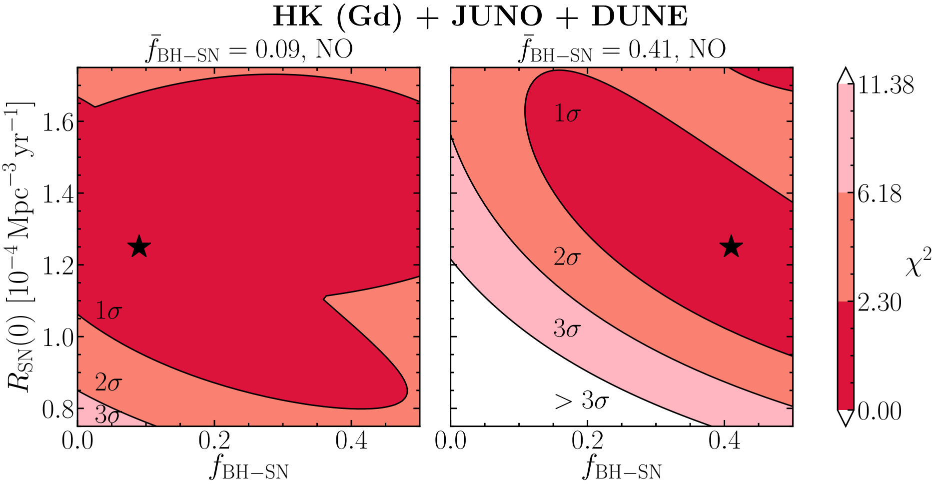
- The high uncertainty comes from $f_{\mathrm{BH-SN}}$–mass accretion rate degeneracy
- DUNE is sensitive to neutrinos $\rightarrow$ helps to reduce the uncertainty

Expected 1σ uncertainty: local supernova rate



Relative error of 20%-33% independent of the mass ordering.

Determining the supernovae unknowns with DSNB



Conclusions

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- Future neutrino detectors will detect and measure the DSNB
- The DSNB
    - is sensitive to the fraction of BH forming progenitors
    - is sensitive to the local supernovae rate
    - shows weak discriminating power of the neutrino mass ordering

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Thank you!